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11.—MINERALOGY OF THE FINE SAND FRACTIONS OF SOME AUSTRALIAN SOILS.

By DOROTHY CARROLL, B.A., B.Sc. (Hons.).

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I.—INTRODUCTION.

This paper describes a series of investigations carried out on the fine sand fractions of soils with the object of correlating their mineral constituents with soil types. The work was done in the Department of Geology, University of Western Australia, during the latter part of 1930 and throughout 1931.

DISTRIBUTION OF SOIL ZONES IN AUSTRALIA.

The soil zones of Australia have been tentatively mapped by Prescott (17, p. 124),[1] who divides Australia into the following zones:—

1. *Desert* (sandy).—Formed under arid conditions; sand ridges, etc.
2. *Desert Steppe.*—Formed under arid conditions and may be sandy or stony.
3. *Mallee.*—Alkaline soils formed under low rainfall ranging from 10-15 inches; the rain falls in the winter. The soils vary from sands to clays and show an accumulation of calcium carbonate in the subsoil at a depth of from 8 to 20 inches. pH is about 8. (24, p. 83.)
4. *Brown Earths.*—Less alkaline than the Mallee soils, and developed under rainfall of 15-25 inches. 6.0 to 7.5 appears to be the pH range. Bases and sesquioxides are leached and distributed throughout the profile. (24, p. 83.)
5. *Chestnut Earths.*—Formed under fairly arid conditions, alkaline bases are leached and alkaline earth bases accumulate; little organic matter formed.
6. *Black Earths.*—Very similar to the Chestnut Earths but formed under slightly less arid conditions with the accumulation of organic matter.
7. *Podsolised Soils.*—Formed under fairly high rainfall conditions which cause leaching of the bases and sesquioxides to a lower horizon where they may accumulate as a pan. Reaction is on the acid side.

In mapping the soil zones of Australia, Prescott has followed the Russian agriculturalists in basing his map upon climatic considerations (9, p. 8). In each soil zone the climatic agencies have worked together to produce soils having more or less closely related characteristics. Within each soil zone there are recognised normal soils which have developed from known igneous or sedimentary rocks, such as granite, sandstone or shale. In these local types the minerals present in the fine sands will reflect the mineralogical character of the parent rock, modified by the weathering to which it has been subjected. Transported soils of any kind will contain minerals which may differ widely from those of the rocks on which they happen to be resting (16, p. 464). These minerals may be conspicuously rounded, and an examination of the grains microscopically may indicate the amount of wear to which they have been subjected (4, p. 668). The grains of loess soils, however, do not show this rounding, because they have been carried in suspension great distances by the wind.

[1] Numbers refer to the bibliography.

From a consideration of the minerals composing acid and basic igneous rocks, it will be seen that the proportion of heavy to light minerals in the fine sand fraction will show whether the soil has been derived from granitic or basic rocks. Soils derived from basic igneous rocks have a larger amount of heavy minerals in the fine sand than those derived from acid igneous rocks or from sedimentary rocks.

Soils resulting from the weathering of metamorphosed sediments may resemble in mineralogical character soils from acid or basic igneous rocks, depending on the original nature of the sediments. Characteristic metamorphic minerals such as kyanite, sillimanite, and staurolite may be present.

There are, in addition, soils which are thought to be abnormal in that they do not show the characteristic features of the zone in which they occur. Such, for example, are the lateritic soils now forming from ancient laterites which are thought to have been themselves once soils developing under warm, moist climatic conditions. These lateritic soils retain some of the characters of true laterites which could not develop with the present climate in the southern part of the continent (15, p. 534). The lateritic soils have an acid reaction which is believed to have persisted from the earlier period of formation of the original laterites (24, p. 82). In other words, the soils are endodynamomorphic or immature, the present climatic conditions not having been continued for a sufficient length of time to make much impression on the soil. Lateritic soils cover wide areas in Western Australia, and, as they are infertile, present a very real economic problem. Careful investigation is needed before the relationship between the soil and the original underlying rock can be worked out mineralogically.

Another type of immature soil is the Rendzina, or lime-humus soil, which is developed on the chalk at Gingin, W.A. This soil gives an alkaline reaction in a soil zone where the reaction should be acid (24, p. 84).

II.—METHOD OF INVESTIGATION.

A.—SOURCE OF SOIL SAMPLES.

As far as possible, the soils examined were from areas where soil surveys have been made and represent profile samples (18, p. 9; 19, p. 32; 9, p. 9-12). A profile sample is one which has been obtained from a definite horizon in a vertical section from the surface of the soil to the underlying rock.

The fine sand fraction of a soil contains the particles ranging from 0.2-0.02 mm. in the International System of Mechanical Analysis (18, p. 10). It has been found that this is the best fraction for the examination of the mineral constituents (13, p. 260).

The fine sands used for this investigation were obtained from the following sources:—

(1) Samples collected by Dr. L. J. H. Teakle, Department of Agriculture, Perth, W.A. Mechanical analyses of these were made by Mr. B. L. Southern, A.A.C.I., Government Chemical Laboratory, W.A.

Esperance, W.A.
Lake Brown, W.A.
Lake Kathleen, W.A.
Lake King, W.A.

(2) Samples collected by Dr. Teakle, the mechanical analyses being carried out by the author, using the Kuhn cylinder method.
Isseka, W.A.
Peak Charles, W.A.

(3) Fine sands of soils mechanically analysed in the Government Chemical Laboratory, W.A.
Dajoing, W.A.
Nornalup, W.A.

(4) Fine sands of soils mechanically analysed at the Waite Institute, Adelaide, and kindly sent over by Professor J. A. Prescott.
Auburn, S.A.
Clifton, Q.
Coomealla, N.S.W.
Forth, Tas.
Glen Osmond, S.A.
Kuitpo, S.A.
Lyonville, Vic.
Merriwa, N.S.W.
Meteor Downs, Q.
Mirrool, N.S.W.
Mount Barker, S.A.
Mt. Gambier, S.A.
Renmark, S.A.
Roto, N.S.W.
Yurgo, S.A.

(5) Samples collected by Mr. R. T. Prider, B.Sc., mechanically analysed by the author.
Jimperding, W.A.
Narrogin, W.A.

(6) Samples collected and mechanically analysed by the author.
Augusta, W.A.
Alexandra Bridge, W.A.
Bunbury, W.A.
Donnybrook, W.A.
Kulikup, W.A.
Katanning, W.A.

Soil Sample Localities.—The localities from which soil samples were obtained were placed on Prescott's map in order to show the soil zones in which they occur. In Part IV. of this paper the latitude and longitude of the sample localities have been added, so that by referring to Prescott's map (17, p. 124) the soil zones in which they occur can be readily ascertained.

In the earlier stages of this work a map was constructed showing isohyets, soil zones, and geology. Since, however, the mineral content of soils is largely dependent on the mineralogical character of rocks, and not on their ages, it soon became apparent that the information supplied by a general geological map was of very little significance in pedological problems. For a geological map to be of any value in soil work the details supplied should be of a petrological rather than of an historical character.

B.—IDENTIFICATION OF MINERALS AND EXPRESSION OF RESULTS.

The usual procedure of preparing the samples before the microscopic identification of minerals consisted of cleaning with dilute acid (oxalic acid gave the best results), washing, drying, and separating into light and heavy fractions by means of bromoform (S.G. about 2.9). Where there was a large amount of heavy fraction, an electro-magnetic separation followed, but was not entirely satisfactory, as it was found that any one mineral varied in magnetic properties from sample to sample and separation by the electro-magnet was discontinued. It was found that some samples could be separated into light and heavy fractions sufficiently well by panning. The basaltic soils from the Eastern States received this treatment.

For the microscopic identification of the minerals part of each fraction was mounted in clove oil of known refractive index (1.53 was found satisfactory). After a rapid glance over the mount, any minerals not easily identified were removed, and the refractive index determined by a set of refractive index liquids (14, p. 15). A useful test for refractive index was made with the Leitz petrological microscope by introducing a shadow above the objective with the brass edge of the mica or gypsum plate. If the mineral tested has a higher refractive index than the liquid surrounding it, the edge nearest the shadow becomes dark, and if lower than that of the liquid, the nearest edge becomes white or very light, and the further edge dark. The test is quickly made and will show very small differences in refractive index. If the surrounding liquid and the mineral are of very nearly the same refractive index, a blue colour appears on one side of the mineral grain and a yellow colour on the opposite, when the shadow is introduced. This method has been found very useful where a large number of grains have to be dealt with fairly rapidly, as in traversing across a light fraction of quartz and felspar.[2] The minerals were identified by the usual optical tests, and comparisons made with a standard set of detrital minerals.

Method of expressing Results.

In order to obtain some idea of the relative abundance of the minerals present, the method set out in Milner's Sedimentary Petrography, p. 386, has been followed, but it would have been better to have counted the number of grains of each mineral present in each mount. The figures given in Table I. are based on Milner's method and give the relative proportions of mineral species present, but are not very definite, as they are a personal expression of the relative abundance.

The following scheme has been adopted from Milner:—

Term—	
Flood	9
Very Abundant	8
Abundant	7
Very Common	6
Common	5
Scarce	4
Very Scarce	3
Rare	2
Very Rare	1
Present	P

[2] This method cannot be employed with every type of petrological microscope.

C. Relation of Light to Heavy Fractions.

It has not been found possible to determine the relative amounts of light and heavy fractions. It was hoped that the percentage by weight of the heavy mineral fraction could be obtained by weighing the sample before separation with bromoform and weighing the light fraction after separation, washing and drying. But the separation, however carefully carried out on the small samples many of which only weighed about 2 grams, always left some of the heavy minerals attached by surface tension and interlocking of grains to the light fraction, and some of the light fraction always remained sticking to the rubber tubing used at the ends of the separating funnels. The weight, obtained by difference between the light fraction and the total sample, was unreliable and gave a false idea of the heavy mineral contents. With larger particles the separation would probably have been less liable to error.

For this reason it would be misleading to make any definite statements about the relative proportions of heavy and light fractions, but in all the samples examined, except those from basaltic soils, the heavy fraction obtained from about 2 grams of find sand has been very small in quantity, often being only sufficient to spread thinly under a circular cover-glass.

The usefulness of accurate determination of the proportion of light to heavy fractions is connected with fertility problems. A soil consisting mainly of quartz grains is of low fertility, whereas basaltic soils which are of proved fertility, have a high proportion of heavy to light fractions. But the quality as well as the quantity has to be taken into consideration.

The amount of heavy fraction is important in assisting in the distinction between granitic soils and basic igneous rock soils. There are many gradations between the two types, but where there are underlying granitic rocks, from which the soil above them was formed (sedentary soils), only a very minute amount of heavy fraction is obtained. When further investigations have been made this may have an important bearing on the geological mapping of obscured areas. Rocks containing any special mineral could readily be traced by the mineral content of the overlying soil. (21 p. 499.)

III. MINERALOGY OF THE FINE SANDS.

A. Description of the Identified Minerals.

In the appended tables the heavy minerals have been placed in six groups, the first five of which are based on the chemical composition of the minerals. The sixth group contains miscellaneous minerals placed together for convenience. The light minerals are grouped separately. The same grouping has been followed in the description of the minerals. The following characteristics of the minerals identified are those which were observed in the samples examined.

Titanium minerals.

Ilmenite: Black, opaque; often covered with leucoxene, but when this is absent the lustre is metallic. Rounded to sub-angular; crystal faces scarce.

Leucoxene: White to pale yellow, rounded, opaque grains.

Rutile:

(a) Red-brown, rounded, stumpy prisms; geniculate and arrowhead twins are found, but are not common.

(b) Yellow, slender, acicular prisms often with sharp edges and capped by pyramids.

The yellow variety may be developed in situ, the red being derived from the parent rock.

? Sphene: Yellow grains often with small crystal faces, non-rounded.

Anatase: Colourless to yellow; in flat, rectangular crystals with bevelled edges; sometimes slightly rounded. Also in small, acicular prisms growing together. Anatase is nearly always authigenic. (16, p. 445; 3, p. 24; 6, p. 334.)

Iron minerals.

Hematite: Small, red-brown flakes with high refractive index.

Limonite: Rounded earthy grains; coats many mineral grains.

Magnetite: Small, rectangular to rounded grains; black, opaque with metallic lustre.

? Pyrite: Brass-yellow, opaque masses, often with grooved surfaces.

Epidote group.

Epidote: Yellow-green cleavage and broken fragments, some slightly rounded; moderately pleochroic; refractive index high.

Ferromagnesians.

Hornblende:

(a) Dirty, green-brown, pleochroic cleavage fragments.

(b) Blue-green, small, irregular, very pleochroic fragments.

(c) Practically colourless grains of fairly large size.

Augite: Yellow-green to pale brown-green grains, often somewhat rounded. Character is fairly constant through a large number of samples.

Mica group.

Biotite: Pale brown, basal fragments; edges often corroded.

Muscovite: Colourless, basal fragments yielding excellent interference figures; edges uncorroded in contrast to biotite.

Miscellaneous group.

Garnet: Colourless to pale pink and brown; most grains are broken fragments and non-rounded; surface of some grains mammilated.

Tourmaline:

(a) Brown-green, sharp-edged, small prisms.

(b) Rounded, fairly large basal sections; blue, brown, green or gray.

(c) Stout prisms, pleochroic pink to green.

(d) Ragged, irregular, blue flakes; weakly pleochroic.

Pleonaste: Bright green to pale yellowish-green (Lake Brown soil), isotropic grains, slightly rounded; not a common mineral of soils.

Andalusite:

(a) A single prismatic grain with dark inclusions was noted in the Lake Kathleen soil.

(b) Large, colourless, broken fragments showing good figures; very slightly pleochroic.

? Topaz: Colourless, broken grains.

Kyanite: Colourless, cross-fractured grains.

Sillimanite: Colourless, elongated grains with parallel extinction and low interference colours; some grains in fibrous aggregates.

Zircon:

(a) Stumpy, rounded prisms capped by pyramids; colourless to yellowish.

(b) Zoned, prismatic grains; inclusions common; often brown to yellow.

(c) Twinned crystals; geniculate twins of colourless stumpy individuals, not at all common.

(d) Fine, acicular, colourless, usually clear cystals sometimes containing a few dark inclusions; may have been released from biotite. (16, p. 440.)

? Monazite: Yellow-green, rounded grains slightly pleochroic and with high refractive index.

Staurolite: Broken fragments, yellow-brown and pleochroic; one perfect cruciform twin, pale yellow in colour and very pleochroic was found in the soil from Lake Brown, W.A.

? Chlorite: Pale green, irregular masses with low polarisation colours. Obviously a decomposition product.

Light Fraction.

Quartz: The most common mineral of soils. Angular to sub-angular grains, rounded grains rare in most samples. Usually colourless but pale yellow in some samples. Inclusions not very common, but some soils have quartz grains with many rutile needles. Small colourless apatite rods have sometimes been seen as inclusions, but these are rare.

Orthoclase: Occurs in fairly large, rounded grains often clouded with alteration products.

Plagioclase: Small, colourless, rectangular cleavage fragments; twin lamellae when present are very fine. Untwinned plagioclase distinguished from orthoclase by refractive index.

Microcline: Small fragments exhibiting cross-hatching under crossed nicols.

Microperthite: A few cleavage fragments with a fine moiré appearance. Present in a number of soils but always in small amount.

Kaolinised material: Small, rounded grains, yellowish-brown to colourless; somewhat opaque.

Sponge Spicules.

Opaline silica, isotropic. Usually occur in broken pitted fragments. Soils near the coast contain larger and more complete spicules than those farther inland. Spicules are often present in the soil down to a considerable depth (over three feet is common), but in a sample from Lake Brown, W.A., small fragments of spicules were found down to a depth of 11 feet. A mount of the light fraction from Lake King, W.A., was sent to Mr. F. Chapman, of Melbourne, who identified the spicules as the longoxea or principal skeletal of a marine sponge like Ecionema. The smaller rod-shaped bodies probably belong to the same or a related species.

Spicules were found in practically all the soils examined and appear to be commonly present in soils in many parts of the world, though references to their occurrence are not numerous. Javanese soils always contain spicules and other siliceous remains. J. B. Scrivenor reports spicules in a soil in Malaya (Geol. Mag. Sept. 1930, p. 385). The soils of U.S.A. and Holland also contain spicules and other small organic remains, which are dismissed as unimportant (J. K. Plummer J. Agric. Res. V. 1915-1916, p. 569-581; 1, p. 37 & 67).

The suggestion is made here that the spicules in Australian soils have been carried inland by wind, and deposited. Chapman mentions that they occurred in the red rain which fell in Victoria in 1927, and they have been observed, together with other minute remains, in similar circumstances in America. It is curious to find that they occur to such depths (see Table I.), but could perhaps have been washed down by rain. In other countries a recent elevation from below sea-level has been postulated to account for the presence of spicules. 200 feet would be the necessary elevation in Java.

Spicules and other small organic remains are supposed to cause a local disease of horses' hoofs known as "chip-chip," which is much more prevalent in the coastal districts than inland.

In the sample from Isseka, W.A., the spicules are very abundant and range in length from 0.0664 to 0.1311 mms., with an average length of 0.056 mms. Isseka is fairly near the coast. In the Lake King samples the spicules are not nearly so abundant and are very much smaller.

Other organic remains include occasional diatom cases and radiolarian skeletons, but these are not nearly as common as the spicules.

B.—MODIFICATION OF FORM.

In the preceding section, the various forms developed by soil minerals have been summarised. Erosion has an important effect on the form of some minerals, *e.g.*, quartz, felspars, tourmaline, etc., but on others has little or no effect. Zircon in thin sections of rocks is just as likely to be rounded as euhedral, and therefore the occurrence of rounded zircon cannot, in most samples, be used as a criterion of prolonged erosion, and, moreover, rounded and euhedral forms usually occur together. However, the rounding of zircon may sometimes be due to erosion, as in the Esperance (W.A.) soils, in which large rounded zircons, quite unlike those found in igneous rocks, occur with well rounded quartz, tourmaline and a little felspar. Whether the material from which a soil has been formed has undergone long continued abrasion or not will be shown by the amount of rounding which the quartz grains have undergone. Sands from Esperance have been made the subject of a special investigation to determine the co-efficient of roundness as used by the Columbia University (4, p. 668) and the results tabulated.

Tourmaline grains often show a considerable degree of rounding, but here the original form of the grains must be considered, as the sections at right angles to the vertical axis are naturally more easily rounded than prismatic grains.

Garnets are very resistant to erosion, and no truly round grains have been observed, although half-round grains are fairly common.

The felspars wear easily and are often well rounded, while the associated quartz is angular to sub-angular. Chemical decomposition assists the rounding to a certain extent.

Augite and epidote (particularly the latter) are frequently rounded, whereas hornblende splits up into cleavage fragments and is never rounded, as far as observed. Magnetite and ilmenite appear to be rounded by erosion fairly readily, but the latter becomes coated with leucoxene which forms a protective blanket.

Rounding by erosion has some value in suggesting the past history of a soil. It has usually been considered that wind is a more efficient agency than water in the rounding of sand grains, but recent experiments have shown that this idea is erroneous (G. E. Anderson, Jour. Geol., Vol. 34, 1926, pp. 144-158). Phillips (Q.J.G.S. 1881) first gave prominence to the aeolian origin of "millet seed" grains, and from this the conception developed that the wear of sand grains by water was a slow process when compared with similar wear by wind. Water has been considered less effective than wind in the rounding of sand grains because of the surface tension of the film of water supposed to surround sand grains while submerged. This film, according to Goodchild ("Desert Conditions in Britain") serves as a cushion which prevents the grains actually coming in contact, or at least retards the force of impact and therefore reduces the rate of wear on the water-worn sand grains. It has been pointed out, however, that sand grains submerged in water cannot be regarded as surrounded by a film differentiated from the body of the water, and that the water will not prevent collision of the sand grains while submerged.

The rounding of grains by mechanical wear is an exceedingly slow process, and it does not appear likely that sand grains in a journey from the centre of a continent to the sea would experience sufficient wear to become rounded, and therefore sub-round and round grains must be of great age. The presence of a greater degree of rounding of grains, as well as a larger number of rounded grains, in recent dunes than on the beach is due to the selective sorting of the wind. Rounded grains are more easily rolled by the wind than the angular and flattish grains which are left on the beach or river flats. Submerged sand grains along the beaches are in constant motion and are free to collide, so that the beach presents the ideal situation for the rounding of sand grains. Dune sands move only occasionally and then only a fraction of one per cent. of the total volume of the dune. Rounding by wind can only occur when the ground velocity of the wind exceeds 10 miles per hour, which corresponds to about 36½ m.p.h. at a height of 130 feet above the ground.

IV.—MINERALOGICAL CHARACTERISTICS OF THE FINE SANDS FROM THE VARIOUS SOIL ZONES.

A.—Notes on the Tables.

The results of this investigation have been placed in two tables.

Table I. gives the locality, soil zone and minerals identified, together with the depth and catalogue numbers of the samples. The Eastern States samples are catalogued by the Waite Institute, while the numbers of the Western Australian samples refer to the Government Chemical Laboratory Catalogue. The catalogue numbers have been added so that if further information is published, it can be connected with that supplied in this paper.

Table II. shows the distribution and persistence of the minerals from the various localities. The approximate chemical composition (from Dana) has been added for convenience of reference.

B.—Soils from Pre-Cambrian Areas.

Practically all the samples from W.A. were from localities situated in areas underlain by Pre-Cambrian rocks. The known rock types represented in the samples are granite, basic igneous rocks (gabbro and dolerite), and metamorphics (gneisses, etc.). The Pre-Cambrian area of W.A. is of wide extent, so that within its boundaries the following soil zones are found:—Mallee, Podsol, Brown Earth. There are also lateritic and alluvial soils, but only a few samples of these were available for examination. Several of the South Australian samples are from localities in the S.A. Pre-Cambrian area.

i.—*Mallee Zone Soils.*

Samples were obtained from Peak Charles, Lakes King, Kathleen, Brown, and Dajoing, W.A. Of these localities, Peak Charles and Dajoing are situated in granitic areas, the latter with small dolerite dykes (Dr. Simpson). Lakes King and Kathleen are also thought to be underlain by granite. Lake Brown, from the character of the heavy mineral content of the soil, is situated in an area occupied by metamorphic rocks. Nearly all these samples give only a very small quantity of heavy minerals. A section of the granite from Peak Charles was made, and it was found that ferro-magnesians and accessories were very scarce, thus accounting for the scarcity of heavy minerals in the soil.

By referring to Table I., the estimated qualitative composition of the heavy fraction of the samples can be seen. The following is a short mineralogical description of the samples:—

Peak Charles, W.A. Lat. S. 33° 5′. Long. E. 121° 15′.

The heavy fraction is characterised by very small amounts of rounded epidote, small flakes of blue-green hornblende, and a few worn prismatic grains of zircon. Microperthite is conspicuous in the light fraction, while plagioclase and orthoclase are plentiful.

Lake King, W.A. About Lat. 33° 10′. Long. 119° 45′.

Heavy fraction is fine grained but of fairly large quantity, containing a good variety of minerals. Ilmenite and leucoxene are in approximately equal amounts; zircon occurs for the most part in large prismatic grains, a few of which are rounded; garnet in pale brown to colourless fragments is rather rare; topaz was doubtfully identified in two of the samples.

Lake Kathleen, W.A. About Lat. 33° 10′. Long. 119° 45′.

More plentiful heavy fraction than in the Lake King samples. Zircon present in small, rounded, brownish grains; tourmaline blue to brownish green; hornblende occurs in yellowish brown and blue-green, small, broken fragments. One grain of andalusite with dark inclusions was identified.

Lake Brown, W.A. Lat. 30° 50′. Long. 118° 28′.

The heavy fraction contained a great variety of minerals, including such typical metamorphic minerals as andalusite, staurolite, and sillimanite. Staurolite occurred mainly in small, broken grains, but in one of the mounts a small, very pleochroic, yellow-green cruciform twin was found. Zircon was fairly plentiful in brown, zoned crystals, somewhat rounded; also a few clear, colourless grains and one green, broken crystal with prisms and pyramid. The quartz in the light fraction contained zircon, rutile, and (?) apatite inclusions.

Dajoing, W.A. Lat. 30° 20′. Long. 118° 5′.

Zircon is the most interesting mineral of the heavy fraction and is present in several forms, the most noticeable of which are geniculate twins; zoned grains are common. Tourmaline is present in both rounded and prismatic grains. Hornblende is in blue-green fragments.

ii.—*Podsolised Zone Soils.*

Samples of podsols were obtained from Augusta, Jimperding, and Nornalup, W.A., and Mount Barker, S.A. The W.A. samples are all from localities situated in areas of metamorphic rocks, the country at Augusta and Nornalup being gneiss, while at Jimperding there is a large variety of rock types, including quartzites and gneisses invaded by basic dykes.

Augusta, W.A. Lat. 34° 17′. Long. 115° 9′.

The soil contained a large amount of heavy minerals of which the following were the most conspicuous: hornblende in dirty, brown-green, cleavage fragments; abundant garnet in large, broken, pale pink grains; ilmenite zircon, and epidote subordinate. Plagioclase accompanied the quartz in the light fraction.

Jimperding, W.A. Lat. 31° 30′. Long. 116° 45′.

The sample represents the panned concentrate from some small alluvial workings for gold. The following features were noted: ilmenite in clean grains, not much coated with leucoxene, and often showing metallic lustre; zircon either in small, zoned, brown grains, or in clear colourless grains, both types were worn prisms; tourmaline in sharp-edged, stumpy, grey prisms; rutile in yellow and red, rounded stumpy prisms. The minerals of the light fraction were not determined.

Nornalup, W.A. Lat. 35° 0′. Long. 116° 30′.

The soil contained a fair amount of heavy fraction, but yielded only a few species. Zircon is very abundant in many types, the most plentiful being colourless, rounded prisms; hornblende in brown-green fragments, some of which are very light in colour; ilmenite and leucoxene in about equal amounts with a little garnet. In the light fraction orthoclase accompanies the quartz.

Mount Barker, S.A. Lat. 35° 5′. Long. 138° 58′.

The heavy fraction consists of tourmaline in abundant, brown, very pleochroic prisms with inclusions; zircon in colourless prismatic and rounded grains; rutile abundant in yellow acicular crystals and rounded, red grains; a little augite, hornblende, muscovite, epidote, and ? sillimanite. The light fraction is made up of quartz, orthoclase and plagioclase.

iii.—*Soils from the Brown Earth Zone.*

Samples of soil from the Brown Earth Zone were obtained from Narrogin, Katanning and Isseka, W.A., and Auburn, S.A. Two samples were obtained from Narrogin, one was above a basic rock, probably a gabbro, while the other was over granite similar to that found in the Katanning district. The soil from Isseka was overlying a basic dyke (dolerite), but microscopic examination showed that it was mixed with soil from adjacent garnet gneiss (see map, 5).

Narrogin, W.A., Lat. 32° 55′. Long. 117° 12′.

The heavy fraction of the soil weathering from granite is noticeable for the abundant zircon; ilmenite is twice as plentiful as leucoxene; a little epidote is present. Orthoclase and plagioclase are both present in the light fraction.

The soil from the basic rock differs from the granitic soil in the greater abundance of epidote, and the presence of leucoxene only in incipient development on a few of the ilmenite grains. Zircon is not abundant and occurs in small prisms with dusty inclusions. Abundant augite and hornblende (dirty green fragments).

Katanning, W.A. Lat. 33° 38′. Long. 117° 35′.

The soil overlies granite, and the main characteristics of the heavy fraction are found in the well-developed leucoxene, plentiful zircon of two types, one clouded with inclusions, the other clear; both types in rounded prismatic crystals. Rutile, hematite and garnet are the remaining heavy minerals. Orthoclase and quartz make up the light fraction.

Isseka, W.A. About Lat. 28° 40′. Long. 114° 45′.

The heavy fraction is noticeable for the small number of species it contains. Ilmenite is the most abundant mineral, followed by pale pink garnet (from gneiss) and brownish weathered augite. The sample resembles that of a basaltic soil, this being accounted for by the similar mineralogy of basalts and dolerites.

Auburn, S.A. Lat. 33° 47′. Long. 151° 2′.

Ilmenite and leucoxene present in practically equal amounts, with well-developed rutile. Magnetite abundant; tourmaline occurs in slender, grey prisms; zircon subordinate; muscovite and biotite in the usual flat plates. Quartz, orthoclase and plagioclase form the light fraction.

iv.—*Lateritic Soils.*

Only two soils of this type have been examined, one from Kulikup, in the Boyup Brook district of W.A., and the other from Kuitpo, S.A. The Kulikup sample was collected on a laterite ridge which has been broken down by long-continued weathering. The soils on either side of the ridge, which is formed by an underlying fine-grained basic dyke, are podsolised soils formed from granite.

Kulikup, W.A. About Lat. 33° 45′. Long. 116° 30′.

There is not a very large amount of heavy fraction and it contains few species. Of these, ilmenite, leucoxene and rutile are abundant, and present in approximately equal amounts. Zircon is in clear, acicular prisms, some of which are rather worn.

Kuitpo, S.A. Lat. 35° 12′. Long. 138° 48′.

The heavy fraction contains a large variety of minerals of which magnetite is very abundant. Ilmenite and leucoxene in about equal amounts; zircon plentiful in small prismatic crystals; tourmaline abundant in pleochroic blue to violet grains, a few brown. Muscovite, epidote and hornblende subordinate. Anatase was doubtfully identified in one sample.

v.—*Alluvial Soils.*

Samples of alluvial soils, the material of which was derived from Pre-Cambrian rocks, were obtained from Alexandra Bridge, Donnybrook, W.A., and Glen Osmond, S.A. The sample from Renmark, S.A., is included here for convenience. The W.A. samples were collected close to rivers distributing the disintegration products of the Pre-Cambrian area.

Donnybrook, W.A. Lat. 33° 0′. Long. 116° 0′.

The heavy fraction is characterised by abundant hornblende in dirty, brown-green fragments, ilmenite, rutile and muscovite; tourmaline subordinate in rather short, stumpy grey prisms.

Alexandra Bridge, W.A. About Lat. 34° 15′. Long. 115° 10′.

Hornblende abundant in dirty, brown-green fragments; ilmenite plentiful; zircon fairly common in prismatic crystals, somewhat rounded; tourmaline subordinate.

Renmark, S.A. Lat. 34° 15′. Long. 140° 30′.

The sample is from a river terrace and contains a fairly abundant heavy fraction. The most noteworthy features are: presence of kyanite and sillimanite, the abundance of tourmaline and the approximately equal amounts of ilmenite and leucoxene, with subordinate rutile and a little biotite. Plagioclase is present in the light fraction.

Glen Osmond, S.A. Lat. 34° 57′. Long. 138° 38′.

The soil is described as a "red-brown loam; wash from Pre-Cambrian." The heavy fraction is characterised by abundant tourmaline in pleochroic pink to green prisms, and also in blue fragments; zircon rather subordinate in small, brown, zoned prisms; leucoxene in excess of ilmenite, with rutile fairly common. Some samples contain andalusite and a little garnet. The micas are well represented. In some samples microcline and microperthite are found in the light fraction.

vi.—*Esperance (W.A.) Soils.*

Three profile samples of a soil at Esperance were examined. Chemically, these soils have all the characteristics of lateritic soils (oral communication, Teakle and Southern; also 24, p. 79), but microscopically appear more like sand dunes. Perhaps the sand has been partly derived from a broken down laterite, the rounding being produced as a result of long continued shifting by wind. Possibly the original "laterite" was formed over an argillaceous sandstone (W. G. Woolnough, Geol. Mag., March, 1930), but from later information it appears that granite is the principal rock in the area.

Esperance, W.A. Lat. 33° 52′. Long. 121° 55′.

The heavy fraction is very small and consists of well-worn grains of brown tourmaline, zircon, limonite, ilmenite and leucoxene. The light fraction consisted principally of well-rounded quartz grains, often filled with slender rutile rods. A little rounded orthoclase accompanies the quartz.

The soil appears to be a dune sand, as the worn quartz grains testify to a second cycle of wear by water and wind.

Esperance Sands.—These sands from the coast inland were examined by the method outlined by F. A. Burt (Jour. Geol. 1929, p. 668). The co-efficient of roundness was worked out by examining the quartz grains under the microscope, and dividing them into the following types:—round, sub-round, half-round, sub-angular, angular. The total number of grains of each type is multiplied by 128, 32, 8, 2 and 1, respectively, the products added, and then divided by the total number of grains examined. Only the quartz grains were examined in order to make the results more uniform.

The Esperance sands consist of clear, colourless quartz, with a noticeable amount of felspar, very subordinate tourmaline, and a little zircon. The quartz often contains sagenite webbing of rutile, some grains enclosing a network of tiny rutile rods.

For comparison, the quartz grains of a dune sand from Bunbury, near the beach, and a sample of normal granitic soil from Peak Charles were examined.

Sample.	Round.	Sub-round.	Half-round.	Sub-angular.	Angular.	Total No. grains.	Coeff. round.
Esperance I. ...	17	120	260	147	7	551	15·24
Esperance II. ...	73	173	284	183	4	717	24·44
Esperance III. ...	94	132	378	197	47	848	23·25
Esperance IV. ...	94	176	297	167	21	755	27·01
Esperance V. ...	128	193	336	109	1	767	33·21
Esperance VI. ...	124	156	358	108	9	755	31·72
Bunbury (dune sand)	42	41	147	88	7	325	24·19
Peak Charles (granitic)	6	28	109	144	78	375	7·74

From the table it will be seen that the coefficient of roundness for the Esperance sands is very much higher than that of a normal granitic soil. The samples apparently approximate to dune sands. Comparison with the figures quoted by Burt shows that these sands would fall into the beach sand group, but this classification cannot be accepted as final, because the standard of grain shape used in America may differ from the standard arbitrarily set up for the purposes of this examination.

C.—BASALTIC SOILS.

Only one basaltic soil from W.A. has been examined. This was the overburden in a small quarry about six miles south of Bunbury. Basaltic soils from the Eastern States ranging from black earths, through red loams, to dark brown soils have been examined. The most noteworthy features of all the samples were the smallness of the grain size, and the large amount of heavy fraction, which often appeared to make up about half the fine sand. The fine sands are all very similar mineralogically, so that brief descriptions only will be given.

Forth, Tas. Lat. 41° 15′. Long. 140° 45′. Red loam.

Clifton, Q. Lat. 27° 38′. Long. 147° 7′. Red loam and black earth.

Meteor Downs, Q. Lat. 24° 21′. Long. 148° 17′. Black earth.

The heavy fractions are made up principally (probably 90 per cent.) of ilmenite with a little magnetite. Leucoxene is absent, but rutile is conspicuous. Augite, tourmaline, and zircon are subordinate.

Lyonville, Vic. Lat. 37° 20′. Long. 144° 15′ (about).

Differs from the above samples by the larger amount of zircon in small, rounded and acicular grains, some containing inclusions. A little biotite is present. The light fraction consists of orthoclase, plagioclase, and quartz.

Merriwa, N.S.W. Lat. 32° 8′. Long. 150° 20′. Black earth.

Leucoxene is absent, the ilmenite : rutile ratio is 9 : 5. Zircon is common in stout, prismatic crystals and broken fragments. Tourmaline, where present, is in slender prisms.

Mirrool, N.S.W. Lat. 34° 15′. Long. 146° 15′. Dark brown soil.

Leucoxene is present, but not abundant, while there is a corresponding decrease of rutile, which occurs in reddish brown, prismatic grains and geniculate twins. Tourmaline common in large, rounded grains. Zircon fairly abundant.

Bunbury, W.A. Lat. 33° 18′. Long. 115° 38′. Reddish brown soil.

Differs from the Eastern States basaltic soils only in the presence of a little brown garnet, epidote and hornblende. Brown tourmaline is common.

On referring to Table I. the association of ilmenite and rutile and the absence of leucoxene in nearly all the basaltic soils is immediately noticed.

The absence of leucoxene in basaltic soils is of great interest since it shows either that:

The soils are too young for leucoxene to develop;

or that:

The conditions for the conversion of ilmenite to leucoxene are unfavourable.

The titanium minerals, ilmenite, anatase, rutile, brookite, sphene and leucoxene, form a series, and if conditions are favourable transformations may take place from one mineral to another. (Clarke, Data of Geochemistry, 1924, p. 355.)

Anatase is considered to be authigenic, *i.e.*, generated in situ at the expense of the other titanium minerals. Rutile may be both allogenic and authigenic, and similarly with sphene and leucoxene. Brammall and Harwood (3, p. 24) have suggested that the authigenic occurrence of anatase and brookite may be due to the alteration of biotite under sour water conditions. By boiling biotite with HCl, the biotitie is bleached and some of the original titania removed. Thus the original fresh biotite contained 1.77 per cent. TiO_2, the partially bleached 1.23 per cent. TiO_2 and the completely bleached residue, 0.61 per cent. TiO_2.

On decomposition the biotite may form a colloidal complex of titania and silica, and these may disengage themselves and become crystalline, the titania forming anatase, while the silica extends and repairs quartz grains and forms new ones. J. van Baren mentions and figures authigenous quartz crystals (1, p. 37; plate 1, figs. 5 & 6).

Ilmenite may alter to granular anatase under similar conditions. The instability of biotite (derived from parent rocks) under certain conditions, has led to the idea that a large number of transparent titanium minerals, such as anatase, may be due to the presence of sufficient biotite in the parent rocks. High porosity and ill-graded sediments favour the development of anatase.

Leucoxenic alteration is at a maximum in coarse sediments. The presence of lime is essential. Where lime is absent or at a minimum, especially in an iron-rich environment, the ilmenite-rutile-anatase-brookite tendency is predominant.

Thus there may be a relationship between the reaction of a soil and the ilmenite-leucoxene ratio.

In the basaltic soils of the Eastern States no leucoxene is developed, but rutile is always present (in the samples examined). This association suggests that in the absence or minimum amount of lime, rutile develops instead of leucoxene. Probably some of the rutile is allogenic. The explanation of the lack of leucoxene in all the samples, except one, may be that the weathering processes have not been continued for a sufficient length of time for the liberation of lime from the ferromagnesians, which would combine with titania to form leucoxene. The samples from Lake Brown and Lake King, W.A., have high pH values (24, pp. 77-78, table), and there are approximately equal amounts of ilmenite and leucoxene.

If lateritic soils owe their acidity to previous climatic conditions, it seems difficult to account for the presence, in both the samples examined, of ilmenite, leucoxene, rutile and sphene, and of anatase in one. An acid environment indicates lack of lime, which suggests that the ilmenite-rutile tendency would be dominant. Sphene and leucoxene indicate neutral or alkaline environment. Sphene appears to be an unstable species in sediments. It may be formed originally in the soil, but owing to chemical instability or unfavourable conditions the sphene-rutile-ilmenite tendency may be promoted. There is too little evidence so far to show whether this would account for the association or not. Perhaps only long continued weathering is indicated with very thorough liberation of lime from the ferromagnesians and original lime-containing minerals.

Summarising, therefore, it appears that—

(a) from the association of the different members of the titanium series, it may be possible to give some indication of the present reaction of a soil and to offer some suggestions as to its mode of development.

(b) The ilmenite-leucoxene ratio alters with age in favour of the latter.

(c) The ilmenite-leucoxene ratio will be of importance in the study of soils from the point of view of past history and nature of weathering, when the matter has been more fully investigated.

D. TERTIARY SOILS.

i.—*Pleistocene Volcanic Ash Soil.*

The sample is from *Mt. Gambier,* S.A., Lat. 37° 51′, Long. 138° 58′, and has a distinctive mineralogical character in the abundant development of anatase, a titanium mineral which, as already mentioned, appears to form in situ where lime is at a minimum. Anatase occurs in flat crystals with bevelled edges and in bunches of small acicular crystals, some of which may be brookite a mineral identical in composition with anatase. Of the remaining minerals of the heavy fraction, leucoxene is slightly more abundant than ilmenite while zircon and augite are subordinate. The light fraction does not give any distinctive features.

ii.—*Tertiary Mallee Soils.*

Samples of soil from the Mallee zone were obtained from three localities in the Eastern States. They are described here for convenience, as there was no information given of the geology of the districts in which they occur.

Yurgo, S.A. Lat. 35° 10′. Long. 140° 5′ (approx.).

The heavy fraction contains a fair variety of minerals, the most abundant of which are tourmaline, ilmenite, rutile, and hornblende. Biotite, augite and zircon are subordinate, the latter present in clear, acicular crystals, some rounded. Plagioclase occurs in the light fraction.

Roto, N.S.W. Lat 33° 11′. Long. 145° 30′.

The heavy fraction contains only a few species, of which brown tourmaline is the most abundant. Ilmenite and leucoxene present in the ratio of 6 : 4. Zircon and amphibole are subordinate. The light fraction consists of quartz and orthoclase.

Coomealla, N.S.W. Mildura district.

The heavy fraction contains a large variety of minerals of which blue and brown tourmaline is the most abundant, muscovite and zircon common, the latter in stout, prismatic crystals. Ilmenite : leucoxene as 5 : 8. Rutile, hornblende and garnet are subordinate. Light fraction consists of quartz orthoclase and plagioclase.

E.—SIGNIFICANCE OF VARIATION OF FORM AND COLOUR OF SOIL MINERALS.

In the petrography of sedimentary deposits it has long been known that certain minerals, generally with characteristic colours and forms, are found in definite horizons (2, p. 26; 25; 26), and in oil-field mineralogical correlation the same has been found, though it is noted as a factor minor in importance to the actual mineral associations. Recently work has been done on the correlation of igneous rock types by means of characteristic accessory minerals (10, p. 235). The results seem to show that most of the accessory minerals are of little use for correlation purposes, and that zircon is the most reliable accessory. This fact seems to be borne out by the occurrence in soils of zircons of special types. The samples from Lake Brown contain a very large proportion of brown zoned zircons. In other localities in W.A. the zircons are clear and colourless with few inclusions. Again, occasional zircon twins have been found, and these only in the soil from Dajoing, W.A. A great deal of careful work is necessary before data of value could be obtained, but the question seems worth further investigation.

Hornblende is a mineral which has various colours. The very blue-green variety may be characteristic of certain rocks while the more common, brownish-green variety will have less value for correlation purposes. Colourless amphibole occurs in a few soils, while it is absent from the majority.

Tourmaline is a common mineral of soils and usually occurs in brown to grey, pleochroic fragments. In a few samples the predominating tourmaline is blue, while pinkish purple tourmaline has also been found. The blue variety may indicate a particular kind of parent rock.

The forms and colours developed by the minerals enumerated above will doubtless be of great value for diagnostic purposes when further work has been carried out and our knowledge of the accessories of the parent rocks increased.

In order to obtain the desired information about the accessory minerals of rocks, it would be necessary to examine crushed rocks, and not rock sections, because the majority of the accessories would undoubtedly be missed in the sections, and in any case, several characteristic features would be lost.

No investigations of this kind have yet been carried out in W.A. and too little is known of the rock types, so far, for any conclusions to be drawn, but an interesting line of investigations is suggested.

F.—SUMMARY.

1. With the exception of anatase, only common rock forming minerals have been identified, but the results agree with those obtained for the U.S.A. (8, p. 292), Dutch and Javanese soils (1, p. 67).

2. Quartz, felspar, ilmenite, leucoxene, rutile, hornblende, augite, tourmaline, and zircon are the minerals of most common occurrence in Australian soils.

3. The ilmenite-leucoxene ratio and the association of the titanium minerals are important.

4. The variation of form and colour of soil minerals may be of use in limiting and diagnosing soil types.

5. Sponge spicules occur in practically every soil examined; other organic remains are not nearly so plentiful.

6. The degree of rounding of the grains, particularly quartz, is important as an aid to distinguishing between sedentary and transported soils.

V.—CONCLUSIONS.

1. The mineral assemblage of the fine sand fractions of soils is strongly influenced by the composition of the underlying rock.

2. The amount and quality of the light fraction is an index of the fertility of the soil.

3. The separation of the heavy minerals of soils may be a quick and useful means of geological mapping where outcrops are scarce or lacking.

4. At present, this method of soil examination does not appear to be of much value for description and correlation purposes. This may be due to the fact that, so far as the Western Australian samples are concerned, too little is known of the detailed geology of the localities, most of which are in the Pre-Cambrian areas. With well defined small areas of known rock types more useful information would be obtained. The basaltic soils examined all appear very similar mineralogically, and show that where similarities undoubtedly exist, they will be readily shown by a microscopic examination. Such an examination of soils will add information to that supplied by mechanical and chemical analyses.

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